Technology Explanation

Attenuation Technology Against Poppet Valve 3D Vibration

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Abstract

We investigated the factors that brought about vibrations of the hydraulic poppet valve with numerical analysis and found a solution to stabilize the behavior of said valve for deployment for production.

Analysis was conducted with non-stationary turbulent flow coupled with a rigid poppet charged with flow forces.

If the clearance between the poppet and the valve seat is small, the deformations of the fluid meshes may be excessive and analysis could diverge.

Therefore, we adopted the mesh superposition method capable of avoiding the constraint of the fluid meshes onto the valve seat and noticeable deformations

Occasionally, the poppet vibrations were supposed to be generated due to a hydraulic jet and eddies born from the jet. We found an "edge tone" and "cavity tone", a continual pressure vibrational phenomena, which caused a large energy poppet vibration.

1 Introduction

Poppet valves are still widely used for many hydraulic machines. They tend to start vibration but no improvement has been taken against the tendency irrespective of their simple structure. It is supposed that turbulent flow around a poppet generates complex fluid load to it, causing unstable behavior. However the cause for the vibration has not been fully clarified due to unestablished measurement technology.

On the other hand, recent progress of fluid analysis tool has realized estimation of complex flow and poppet behavior and a measure against vibration can be taken based on the analysis result.

In this technical report, we introduce our analysis on a coupled model consisting of non-stationary turbulent flow and rigid poppet for finding causes for the vibration of a poppet valve and improving the valve characteristics.

As a cause for the vibration, vortices in the turbulent flow were focused on, and pressure fluctuation was generated in the analysis to identify the mechanism of the vibration of the poppet.

Influence of other causes for the vibration was also investigated and compared with that of the vortices on the vibration.

2 Principle of pressure fluctuation generation by turbulent flow vortex

Here we describe the generating mechanism of pressure fluctuation by a vortex which causes vibration of a poppet valve. The mechanism has been studied as that of sound generation in wind instrument or fluid noise[1)2)].

2.1 Edge tone

Edge tone is a generated sound when a jet flow from a plate-type nozzle collides continuously with a sharp edge as shown in Fig. 1.

When the jet flow collides with the edge, vortices are regularly generated and move downstream. The jet flow between the nozzle and the edge receives influence of the vortices and generates regular vibration in a direction perpendicular to the flow. The vibration frequency is determined by the distance between the nozzle and the edge.

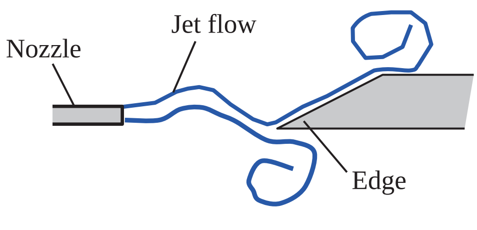

Fig. 1 Edge tone

2.2 Cavity tone

A rectangular empty space in a wall parallel to the flow is called cavity. At the upstream-side edge of the cavity, a vortex is generated when the flow separates from the wall. The vortex moves forward in the free shear layer by the distance of the cavity length and collides with the downstream-side cavity edge. The collision generates a sound wave, which moves backward to the upstream-side edge and generates a new vortex (feedback mechanism). Sounds regularly generated with this mechanism are called cavity tone. Fig. 2 illustrates the cavity and vortices.

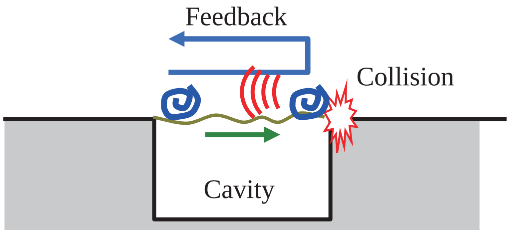

Fig. 2 Cavity tone

3 Coupled vibration model of poppet valve and fluid

In general, a coupled model expresses a poppet and its motion by a boundary surface of movable, deformable fluid mesh set on a flow area. Since all the mesh points on the wall, including the poppet are restricted not to move away from the wall, the mesh deformation could become too large depending on the motion of the poppet and causes calculation failure. In particular, when the poppet is allowed to move in the direction perpendicularly to the axis (hereinafter referred to as transverse direction), interference with a valve sheet located nearby could easily cause the failure. Therefore it is difficult to numerically analyze transverse vibration of a poppet which is observed in actual situations.

In this report, we created a model which does not require constraint on the fluid mesh points on the wall by introducing an overset mesh for the valve sheet independently from the fluid mesh designated in the flow area.

The overset mesh has the following functions and constraints.

(1) It can control the flow as movable wall independent from the flow mesh in the flow area.

(2) Preset motion (such as pump rotation) can be designated to the mesh.

(3) Receiving the fluid force, it can produce a motion according to the force.

(4) Motion constraint due to a mechanical external force, for example when contacting other objects, cannot be made. (The overset mesh slips by the objects.)

This overset mesh realizes analysis of transverse motion and collision with the valve sheet, in addition to the motion along the poppet axis. However, the constraint 4) results in a collision motion constraint on the poppet.

Fig. 3 shows configuration of the fluid mesh and overset mesh and Fig. 4 the model structure of the poppet valve. The poppet valve model in Fig. 4 is the original one, having a shape for which an anti-vibration measure is not taken.

4 Estimated cause for vibration

The followings are empirically estimated causes for the vibration of the poppet and their influences to the vibration are analyzed. Fig. 5 shows the parts to which the causes are relevant.

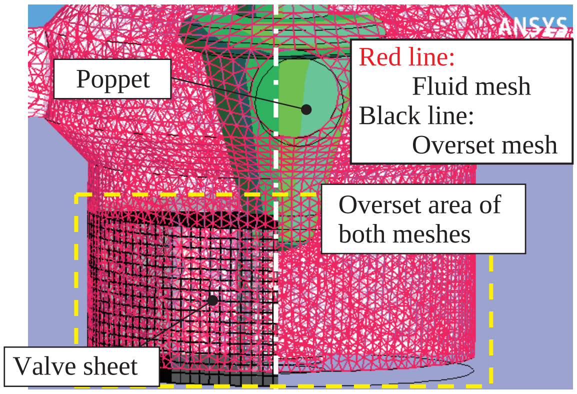

Fig. 3 Configuration of fluid mesh and overset mesh

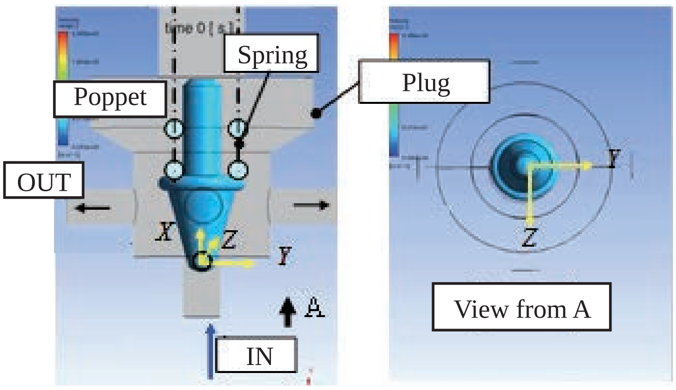

Fig. 4 Poppet valve model (original model structure)

Cause (1) Collision of jet flow with drain port
Cause (2) Eccentric axis of poppet
Cause (3) Collision of jet flow with the wall of drain manifold block
Cause (4) Collision of jet flow with poppet apex
Cause (5) Occurrence of cavitation
Cause (6) Back pressure fluctuation
Cause (7) Air mixing

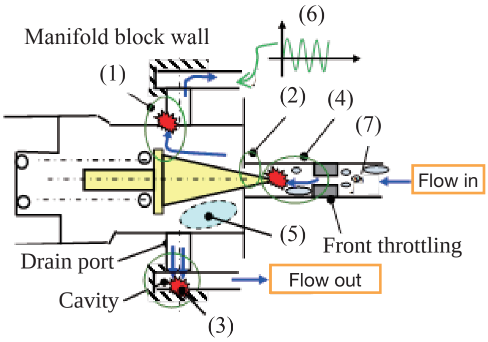

Fig. 5 Estimated vibration causes (parts of causes (1) to (7))

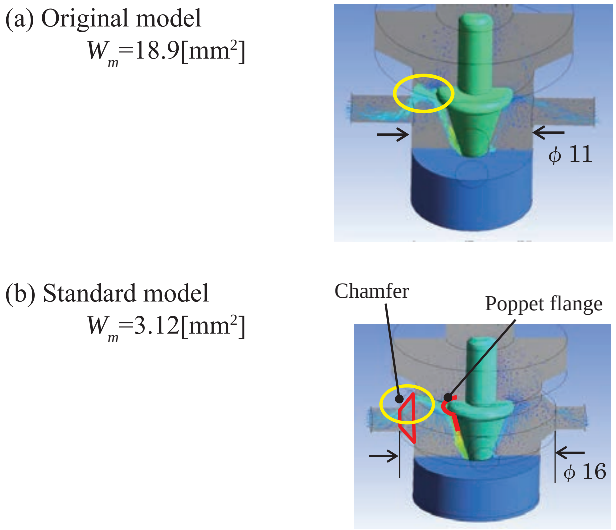

Fig. 7 Difference of flow velocity distribution between with and without chamfer

5 Results of analysis

5.1 Cause (1) Collision of jet flow with drain port

Fig. 6 shows analysis results of the poppet displacement as a function of time and a function of frequency. Fig. 7 shows jet flow velocity distribution over the area from the poppet to the drain edge.

With the original model, it was observed that large vibration was generated by the edge tone mechanism due to the jet flow collision from the poppet flange to the drain port. A chamfer was then introduced around the drain port and its anti-vibration effect was studied. The experiment showed that the chamfer suppressed the magnitude and frequency of the transverse vibration. The flow speed analysis indicated that the reduction occurred because less jet flow reached the poppet due to the displacement of the edge position and the distance between the flange and the edge became larger.

The effect of the chamfer was confirmed in experiments and widely used for current type of mass-produced products. Hereinafter we referred to the model with the chamfer as standard model and effects of other estimated causes for vibration (Fig. 5) on the model are investigated.

The vibration energy Wm in Eq. (1) was applied to the evaluation of the poppet vibration magnitude.

$$W_m = \int_0^F \left\{ I_x(f) + I_y(f) + I_z(f) \right\} df \tag{1}$$

F : Maximum frequency for evaluation (3[kHz])
$I*$: Power spectral density of displacement in each direction

5.2 Cause (2) Eccentric axis of poppet

One can consider that the eccentric axis of poppet could break the symmetry of the edge tone of the cause (1) and hence cause transverse vibration. Considering the eccentric axis of a spring of actual valve, we assumed

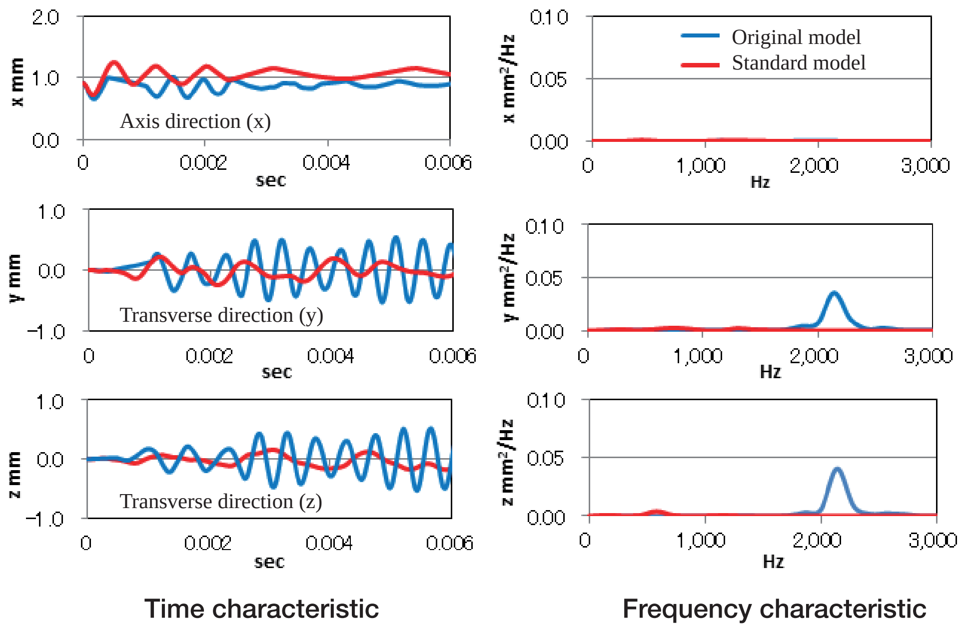

Fig. 6 Cause (1) Analysis results of poppet displacement

application of a constant eccentric axis load of 10 [N] (which corresponds to the eccentricity of 1.7 [mm]) in the y-direction and analyzed vibration (Fig. 8). The load enhanced the vibration in the direction of eccentricity and the vibration energy increased by about 80%.

5.3 Cause (3) Collision of jet flow with the wall of drain manifold block

A manifold block wall was installed in the downstream side of the drain port (Fig. 9), and the effect, on the poppet vibration, of the cavity tone mechanism where a jet flow separating at the outlet of the drain port collided with it was analyzed. Fig. 10 shows the poppet vibration analysis results for the channel gap of the manifold block drain of t0.7, t1.4, and t2.8. For t0.7 and t1.4, the cause (3) gives larger vibration energy of the poppet than the other causes.

For t2.8, on the other hand, the cause (3) gives one third of the vibration energy given by the cause (1) or (2), which indicates the effect of the larger distance to the wall. Namely it was found that large enough gap could effectively suppress the vibration.

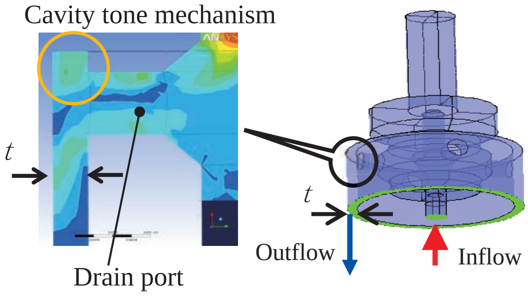

Fig. 9 Model with manifold block and cavity vortex

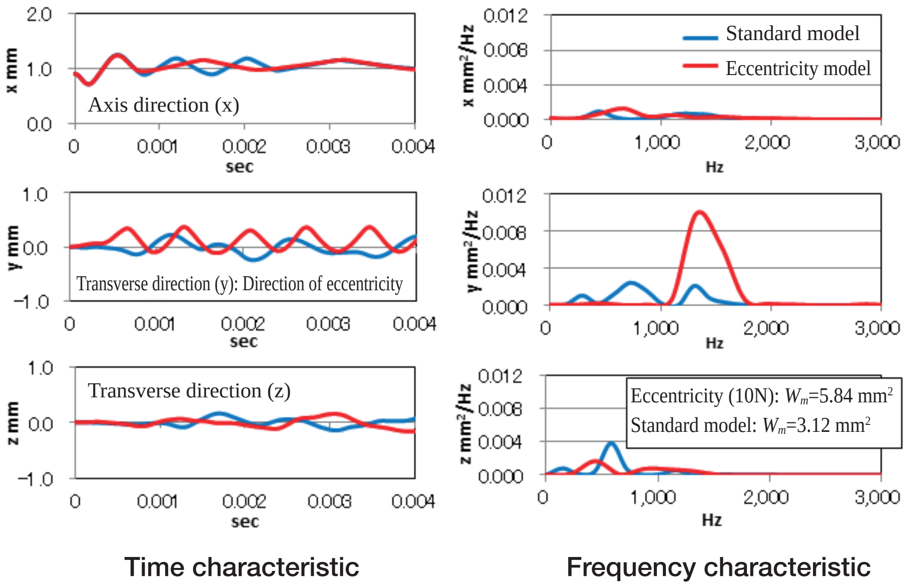

Fig. 8 Cause (2) Analysis results of poppet displacement

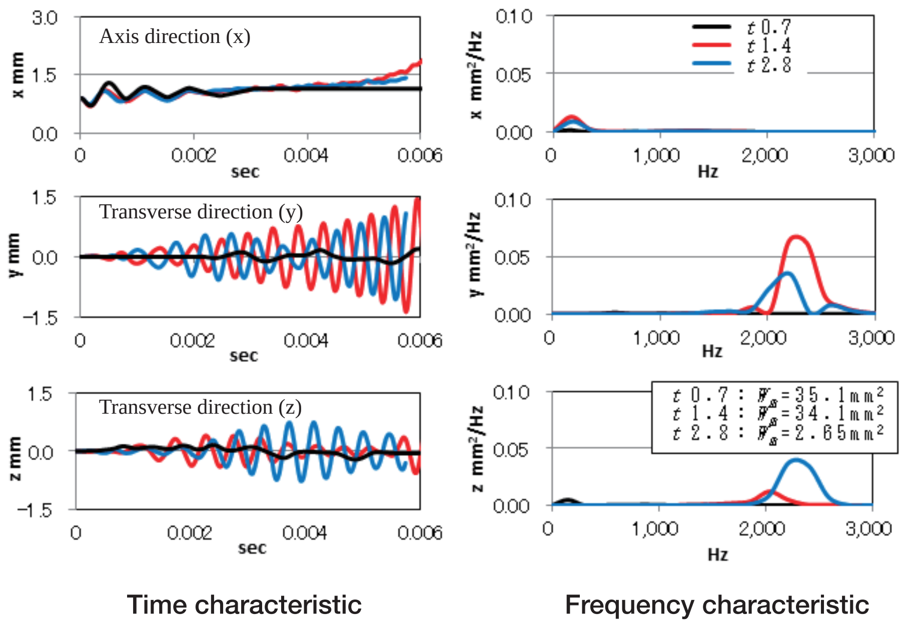

Fig. 10 Cause (3) Analysis results of poppet displacement

5.4 Cause (4) Collision of jet flow with poppet apex

One can easily imagine that a jet flow from the front throttling (orifice on the upstream of the poppet) collides with the apex of the poppet and the edge tone mechanism is generated to cause vibration. Change of the magnitude and frequency of the vibration depending on the distance between the throttling and the poppet can be estimated from the relation with the potential core length of the jet flow (distance from the outlet of the front throttling to the point where the flow speed at the front throttling outlet disappears in the sectional flow speed distribution of the jet flow). In the analysis, the front throttling outlet distance L' was set to 5, 7.5, and 10 [mm] (Fig. 11). The front throttling diameter was not changed from the current type of valve.

Fig. 12 shows the poppet vibration analysis results for different front throttling distances. Transverse vibration was induced by the edge tone and the dependence of the vibration magnitude on the distance L' was determined by the relation with the potential core. (See Wm in the figure. The vibration energy is largest at around the potential core vanishing point L'=7.5 [mm].) However the frequency did not change much and there was no clear indication of the feedback phenomenon.

5.5 Cause (5) Occurrence of cavitation

A 3-phase flow (liquid, vapor, air) was assumed in the fluid model and the liquid phase was assumed to have two components, hydraulic oil and dissolved air. For the oil, we assumed paraffin type hydrocarbon. The temperature of the fluid was set to 25 °C in the analysis. Fig. 13 shows the vibration analysis results of the model and the standard model. The occurrence of cavitation did not enhance but slightly suppressed the poppet vibration.

5.6 Cause (6) Back pressure fluctuation

A sinusoidal fluctuation of downstream pressure of all the four drain ports was assumed to analyze influence of the fluctuation on the poppet vibration. The back pressure fluctuation in the form of a sinusoidal wave 1±1 [MPa], about the same magnitude as in actual poppet valve, was given to the drain port outlet of the standard model and the poppet displacement was estimated. The vibration energy was largest at the back pressure of about 1,300 [Hz] (Fig. 14).

Two patterns of the back pressure, 0.5±0.5 [MPa] and 1±1 [MPa], at the frequency of 1,300 [Hz] were given to analyze the influence on the poppet vibration. The upstream pressure was fixed to 29 [MPa]. The result is shown in Fig. 15. The vibration along the axis was large with large pressure fluctuation amplitude because

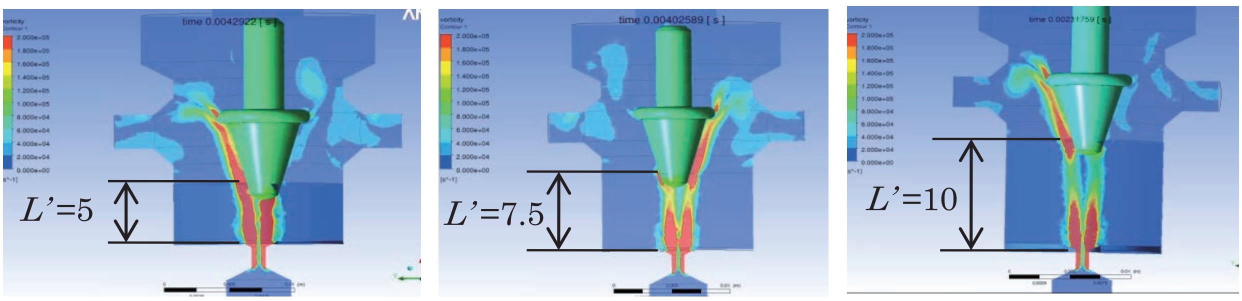

Fig. 11 Front throttling outlet distance and example of vorticity distribution analysis result

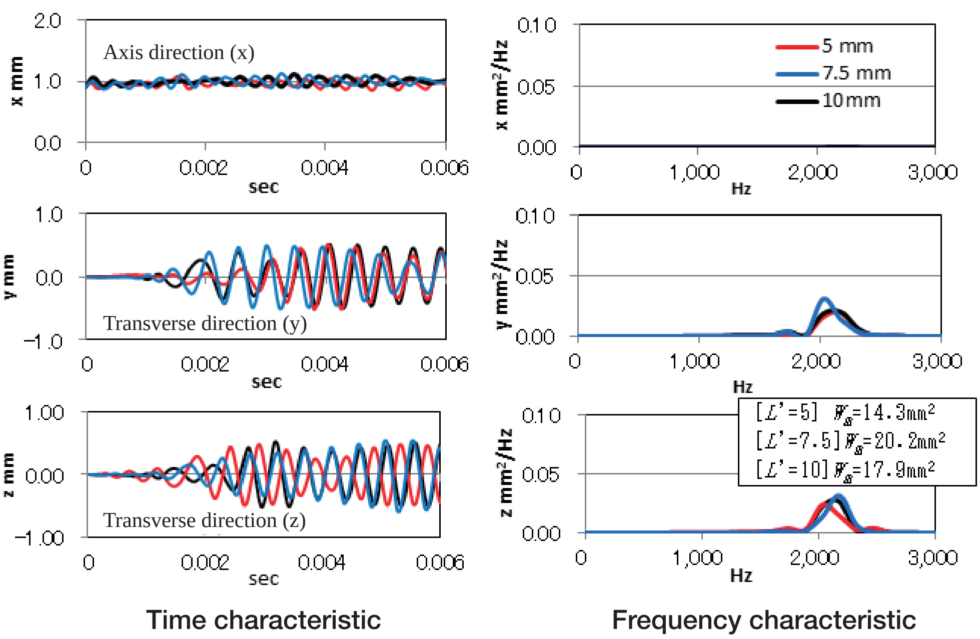

Fig. 12 Cause (4) Analysis results of poppet displacement

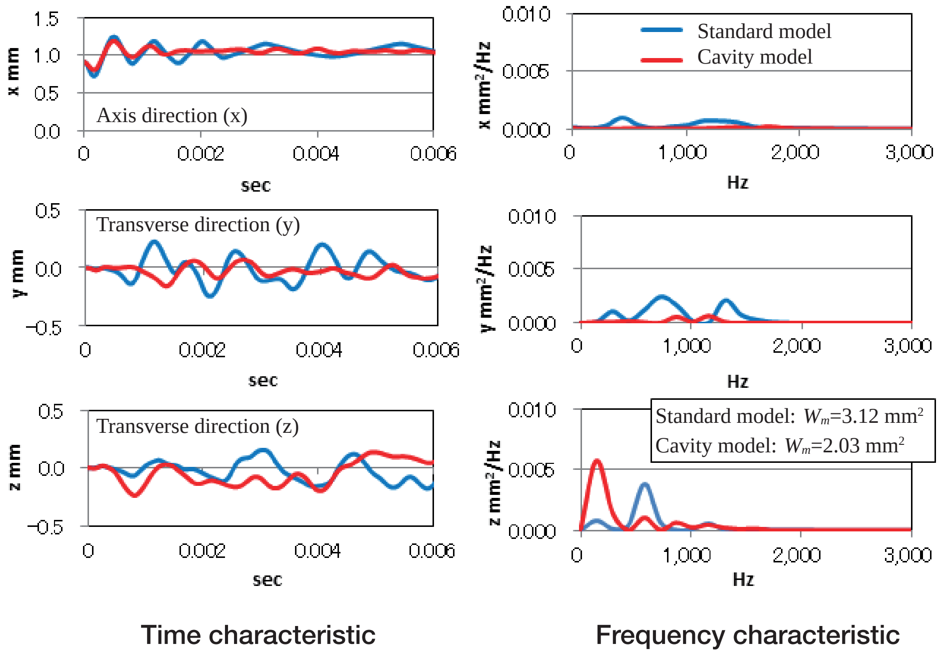

Fig. 13 Cause (5) Analysis results of poppet displacement

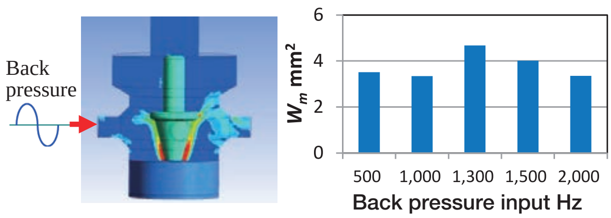

Fig. 14 Input of back pressure fluctuation and vibration energy

a large change in the differential pressure could make a large change in the balanced position along the poppet axis direction. The vibration energy Wm with the back pressure 1±1 [MPa] was about 1.5 times as large as the one in the standard model.

5.7 Cause (7) Air mixing

The poppet motion was analyzed by assuming that the two phase flow with the hydraulic oil and air mixed flows in from the upstream side (Fig. 16). It was assumed in the present model that bubbles had the polydisperse diameter and united with and separated from each other repeatedly. Fig. 16 shows the analysis results with the air volume ratio γ being 0.3 and 0.5 at the inlet boundary. The vibration was larger for larger γ. When γ =0.5, the vibration energy was slightly larger than the energy Wm of the standard model but did not have a large influence. The energy was

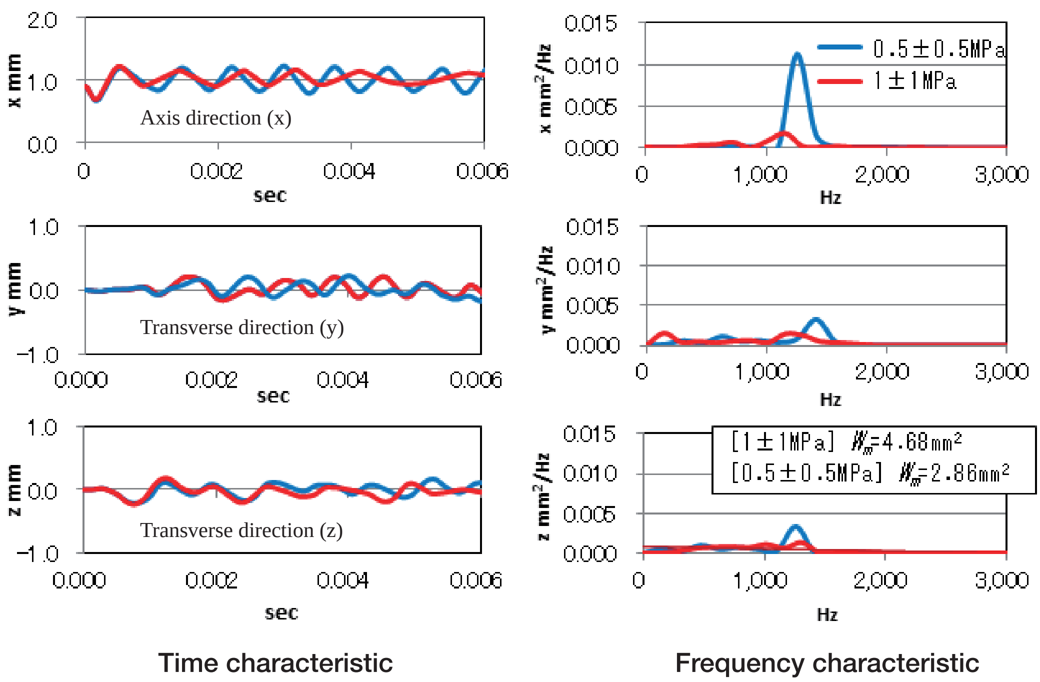

Fig. 15 Cause (6) Analysis results of poppet displacement

also not very large for γ =0.3. Therefore, the vibration could be suppressed depending on the air mixing rate.

6 Comparison of vibration energies caused by estimated causes

Fig. 17 compares the poppet vibration energies caused by the estimated causes, including vibrations generated by vortices discussed above.

From the comparison, one can see the following characteristics.

1. The poppet vibration energy in the original model where drain port collision occurred was 6 times larger than the energy in the standard model where a chamfer was introduced in the port, and had a large influence on the edge tone vibration.
2. The eccentric axis of the poppet caused large vibration in the eccentricity direction, making the energy 1.8 times larger.
3. With the manifold block wall, the cavity tone mechanism was established in the area from the port outlet to the wall surface and caused large vibration (about 10 times larger than that in the standard model) when the wall distance was small (t0.7, t1.4). On the other hand the mechanism's influence was negligible for t2.8, indicating that the vibration was largely dependent on the wall distance.
4. The relation between the distance from the front throttling to the poppet and the poppet vibration energy could be determined by the characteristics of the jet flow and the vibration energy was largest at around the potential core vanishing point (L'=7.5). However a frequency change which indicated occurrence of feedback was not observed.
5. The occurrence of cavitation had little influence on the vibration. It rather suppressed the vibration.
6. The back pressure fluctuation slightly affected the poppet vibration. With the amplitude of 0-2 [MPa] made the vibration energy 1.5 times larger than the energy in the standard model.
7. In the study of the 2-phase model to find the influence on the poppet vibration, the vibration was found larger with larger air volume ratio at the model inlet although it was not very large for γ=0.3 and 0.5.
8. In general the vibration induction effect of the edge tone (causes 1) and 4)) and the cavity tone (cause (3)) was found large. However vibration due to the causes 1) and 3) can be reduced by changing the shape to suppress the jet flow collision.

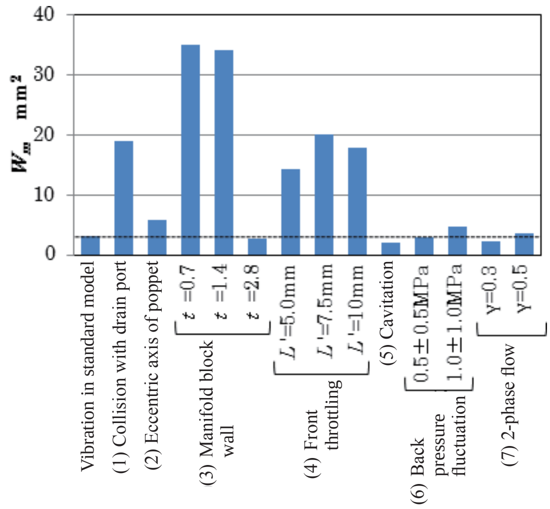

Fig. 17 Energy comparison of vibration generated by estimated causes

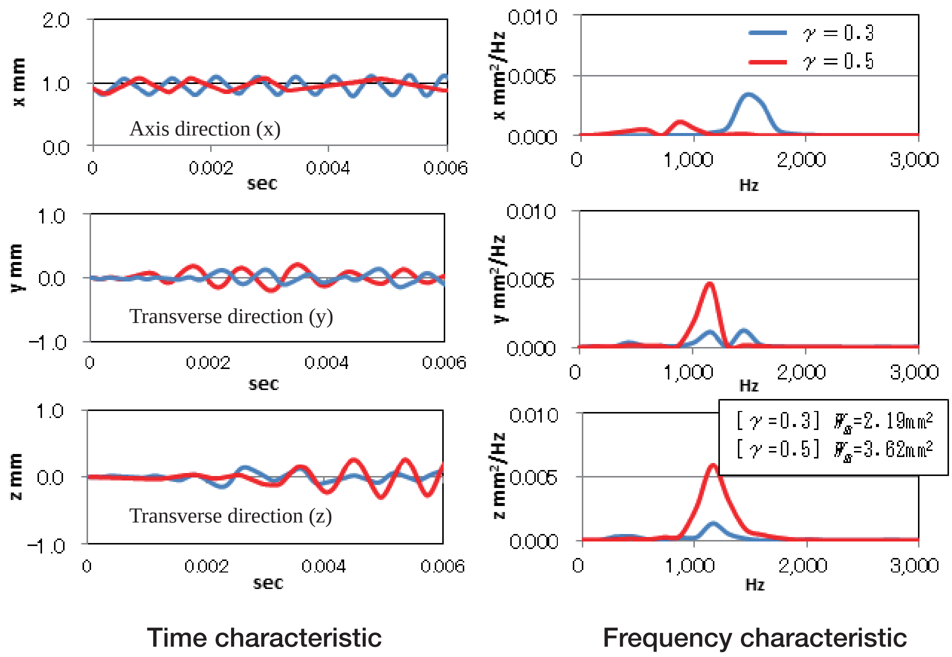

Fig. 16 Cause (7) Analysis results of poppet displacement

7 Conclusions

A coupled model consisting of a poppet valve and non-stationary turbulent flow for three-dimensional vibration analysis with degrees of freedom in the axis and normal-to-axis directions was created and used to identify the causes for vibration, including external disturbance such as back pressure or air mixing. As a result, it was found that the cause (1), cause (4) (edge tone mechanism), and cause (3) (cavity tone mechanism) could generate 4.5-11 times larger vibration energy than the standard model without those causes. As a countermeasure against the vibration, a jet flow collision suppression shape was found. Also, since the overset mesh was found effective on the analysis of three-dimensional vibration, it will be applied to hydraulic machines which require similar analyses.

References

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